21.1 A Wireless Strain Sensing Microsystem with External RF Power Source and Two-Channel Data Telemetry Capability

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High-performance wireless strain sensing microsystems consisting of MEMS strain sensors and interface electronics are critical for advanced industrial applications, such as point-stress and torque sensing for ball-bearings, rotating shafts and blades. The sensed information is important for reliable system monitoring and intelligent control. Stringent performance requirements, including a large input DR, from sub-micro-strain (με) to 1000με over a BW of 10kHz, are required for these applications. Industrial sensing further imposes significant design challenges due to rotating mechanical components which preclude using wire connections. Therefore, stand-alone wireless sensors with remote power and data telemetry capabilities are highly desirable.

In this paper, we present the design, implementation and test results of a wireless strain sensing microsystem, which is powered by an external RF power source and can simultaneously telemeter 2 channels of digitized strain and temperature information to a receiver by passive phase-shift keying (PSK) and amplitude-shift keying (ASK) modulation schemes, respectively. The prototype microsystem achieves the aforementioned stringent performance requirements by using a robust system architecture, a highly-sensitive MEMS capacitive strain sensor, and low noise interfacing and signal processing circuits with a high level of integration.

Figure 21.1.1 presents the overall wireless microsystem architecture, which consists of a MEMS capacitive strain sensor and CMOS interface electronics that are coupled with 2 coil loops for power and data telemetry. The sensor and IC are wire bonded over a silicon base module as shown in the figure. The module occupies a 3mm×7mm area and is attached to a rotating metal shaft surface by an adhesive film. This setup represents a typical industrial sensing scenario. A shaft diameter of 3 inches is chosen for the prototype with an internal coil wound around the shaft and separated from an external coil by one inch. This co-axial configuration is important for ensuring reliable power coupling to the microsystem. RF power transfer is chosen because it is robust and can achieve a sufficient DC power for the desired operation. Furthermore, multi-channel sensor data can be passively telemetered on the same RF link. The rotation of the shaft produces a torque, thus resulting in a surface strain, which can be detected by the MEMS strain sensor. Also illustrated in Fig. 21.1.1 is an SEM of a fabricated silicon MEMS capacitive strain sensor. The device exhibits a gauge length of 1mm and a nominal sensor capacitance of 400fF with a large sensitivity of 283aF/με due to its inherent mechanical signal amplification characteristics [1]. Figure 21.1.2 shows a detailed microsystem functional diagram. The MEMS sensors, modeled as differential capacitors, are driven by a stimulation clock with an amplitude, V_s, of 1.2V and interface with a differential charge amplifier, which converts the sensor capacitance change to an output voltage. A clock frequency of 675kHz is used to modulate the sensor information away from the 1/*f* noise of the amplifier, critical for achieving a high sensitivity. An input common-mode feedback (ICMFB) circuit is designed to suppress any output offset due to the parasitic capacitance mismatch and drift over time [2]. The charge amplifier output is then mixed by the same clock and low-pass filtered to obtain the desired analog strain information. With a low-noise charge amplifier exhibiting an input-referred noise floor of 5nV/√Hz, we have demonstrated a strain sensing resolution of 0.9nε/√Hz with a 3V battery, which is equivalent to a minimum detectable strain of $0.09\mu\varepsilon_{rms}$ over a 10kHz BW [3,4]. The analog strain signal is then digitized by a 2nd-order ΔΣ ADC with an over-sampling ratio of 128 to maintain the system DR. The digitized strain signal is coded with a Manchester code to ensure reliable reception. Although stand-alone MEMS capacitive sensors are insensitive to temperature variations, packaged devices can exhibit temperature dependences due to thermal mismatches between the sensors, packages, and strained surfaces. A CMOS PTAT-based temperature sensor is, therefore, designed for real-time monitoring and system calibration. The temperature sensor output is digitized by a 1st-order ΔΣ ADC with a sampling frequency of 170kHz, coded, and transmitted.

Figure 21.1.3 presents the RF power and 2-channel sensor data telemetry architecture. An external RF power source drives a tuned series resonator consisting of L_1 and C_1. The signal is coupled to a parallel resonator consisting of L_2 and C_2. Previous study shows that an optimal frequency of 50MHz should be used to obtain efficient power coupling by using a 1-turn external coil (320nH) and a 3-turn internal coil (450nH) [5]. The received RF signal is then rectified and regulated to obtain a stable 3V supply with a 2mA current driving capability, adequate for powering the microsystem. The digitized strain and temperature data can be transmitted to a receiver by passive PSK and ASK modulation schemes, respectively. PSK is implemented by modulating the capacitive load across the parallel resonator, while ASK is realized by switching the resistive load at the rectifier output. The reflected impedance, $Z_{Reflect}$, can be demodulated to retrieve the corresponding transmitted data. A quality factor of 10 for the coupled-power LC resonators is chosen as an optimal tradeoff between power coupling efficiency and PSK telemetry data rate [6].

The microsystem electronics are fabricated using a 1.5μm CMOS process. Figure 21.1.4 shows a micrograph of the fabricated chip, which occupies 2.2mm×2.2mm. The prototype system only requires 2 off-chip components: one internal coil and one resonating capacitor. The resonating capacitor can be potentially integrated on chip.

To verify the microsystem functionality operating in a truly wireless fashion, the sensing module is attached to a metal bar surface and subjected to an input DC strain via bending while a 50MHz power signal is applied. Figure 21.1.5 shows the reconstructed output voltage based on the received PSK strain data as a function of applied DC strain spanning ±1000με. The system achieves a sensitivity of 816μV/με with a nonlinearity of 5.2% of full scale. The temperature sensor is characterized from room temperature to 150°C with a sensitivity of 3.8mV/°C and an equivalent resolution of $0.02°C_{rms}$ over a 100Hz BW. The strain sensor is also evaluated by dynamic testing. Figure 21.1.6 shows the received power spectrum when a $10\mu\varepsilon_{pp}$ input signal at 1kHz is applied to the sensor, achieving an average noise floor of -103dBV/√Hz, which corresponds to a minimum detectable strain of $0.87\mu\varepsilon_{rms}$ over a 10kHz BW. The current test setup prevents us from applying larger or higher frequency strain signals. The measured minimum detectable signal is larger than the designed value because the 2nd-order ΔΣ ADC exhibits an increased output noise floor due to coupling of the digital switching signals and RF signals onto the reference voltage used in the converter, which causes a demodulation of the high-frequency quantization noise down to baseband. The measured performance of the wireless microsystem is summarized in Fig. 21.1.7.

References:

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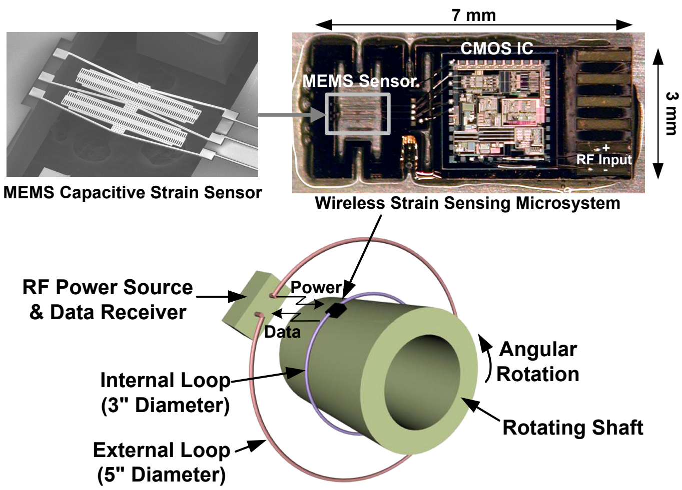

Figure 21.1.1: Overall wireless microsystem architecture.

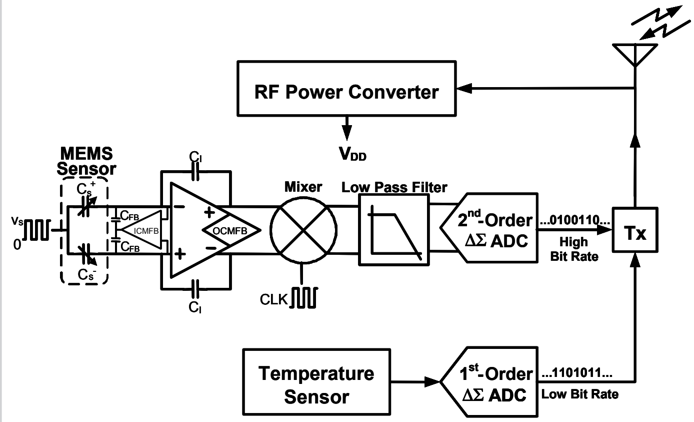

Figure 21.1.2: Detailed microsystem functional diagram.

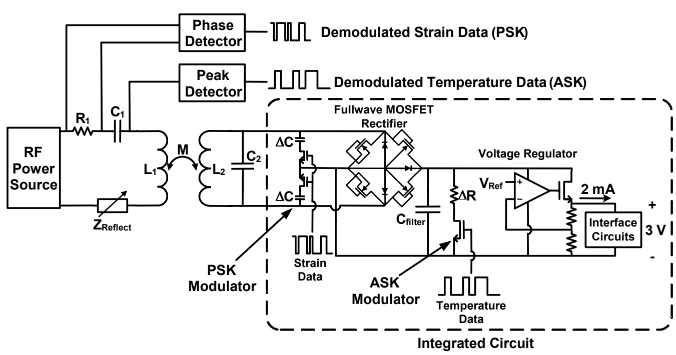

Figure 21.1.3: RF power and 2-channel sensor data telemetry architecture.

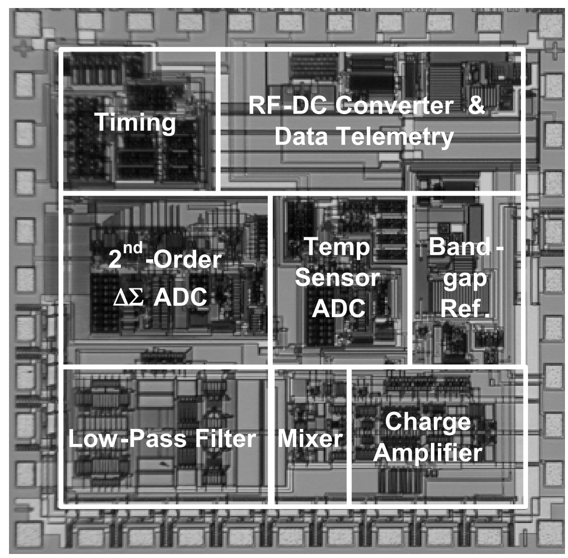

Figure 21.1.4: Fabricated chip micrograph.

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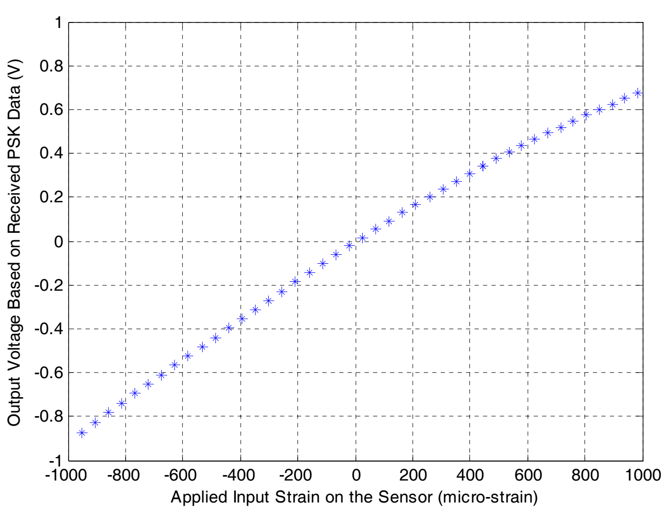

Figure 21.1.5: Received output voltage vs. applied input DC strain on sensor.

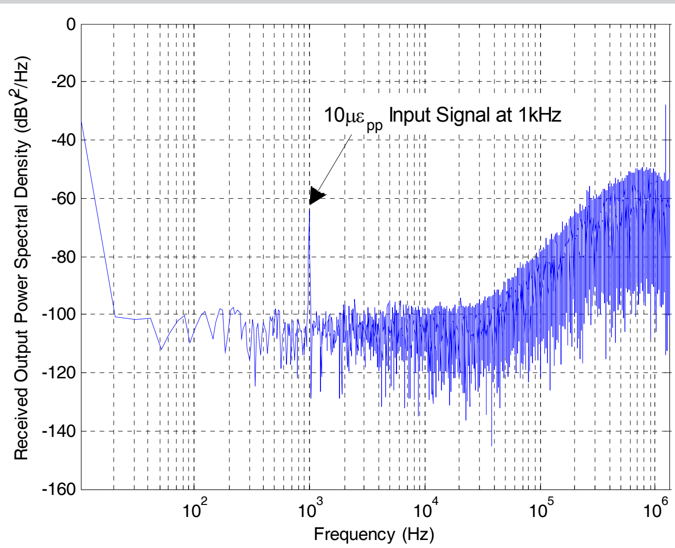

Figure 21.1.6: Received power spectrum of strain sensor under dynamic testing.

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Wireless Microsystem Measured Performance	
RF-DC Powering	50MHz → 3V / 2mA
Number of Sensor Data Channels	2
Strain Sensing Range	+/- 1000$\mu\varepsilon$
Strain Sensitivity	816μV/$\mu\varepsilon$
Minimum Detectable Strain (10kHz BW)	0.87$\mu\varepsilon_{rms}$
Strain Nonlinearity	5.2% F.S.
PSK Manchester-Coded Strain Data Rate	2.7Mbps
PSK Bit Error Rate	$<10^{-7}$
Temperature Sensing Range	25^{o}C - 150^{o}C
Temperature Sensitivity	3.8mV/^{o}C
Temperature Resolution (100Hz BW)	0.02^{o}C$_{rms}$
Temperature Nonlinearity	0.4% F.S.
ASK Manchester-Coded Temp. Data Rate	170kbps
ASK Bit Error Rate	$<10^{-7}$
Total Power Consumption	6mW
System Size	3mm x 7mm

Figure 21.1.7: Measured system performance.

